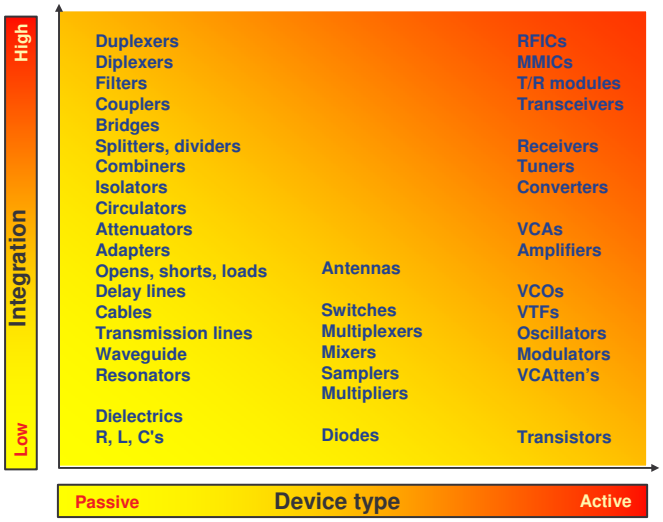
Vector Network Analyzer basics

What Types of Devices are Tested?



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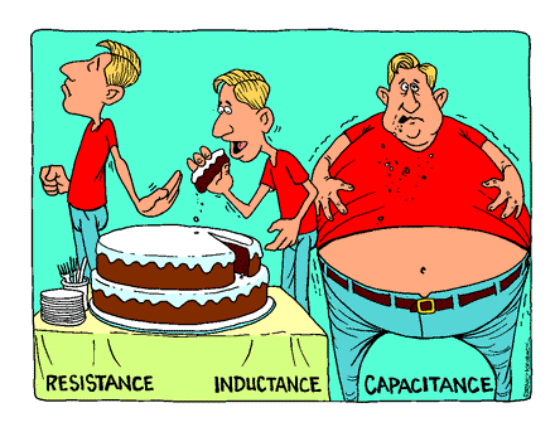
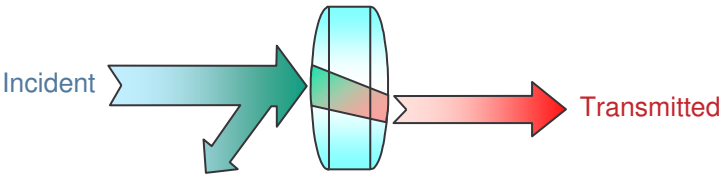
Trasmission lines



Lightwave Analogy to RF Energy



RF

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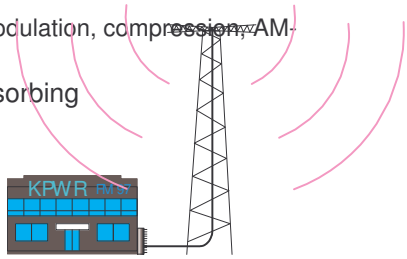
Why Do We Need to Test Components?

- Verify specifications of “building blocks” for more complex RF systems
- Ensure distortionless transmission of communications signals
  - linear: constant amplitude, linear phase / constant group delay
  - nonlinear: harmonics, intermodulation, compression, AM-to-PM conversion
- Ensure good match when absorbing power (e.g., an antenna)



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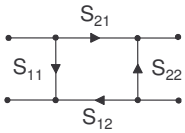
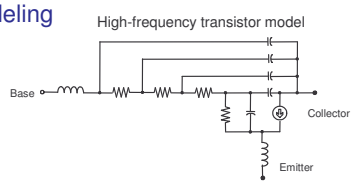
The Need for Both Magnitude and Phase

1. Complete characterization of linear networks

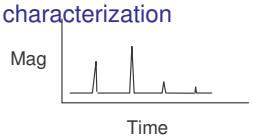


2. Complex impedance needed to design matching circuits

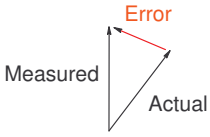
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction



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Transmission Line Basics

Low frequencies

- wavelengths >> wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

High frequencies

- wavelength » or << length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

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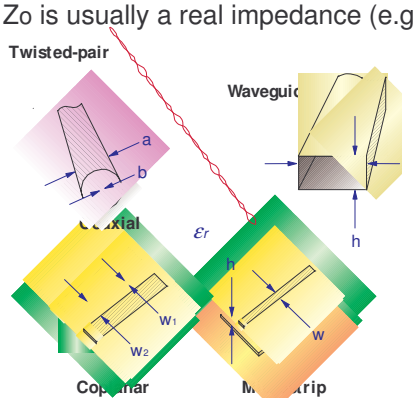
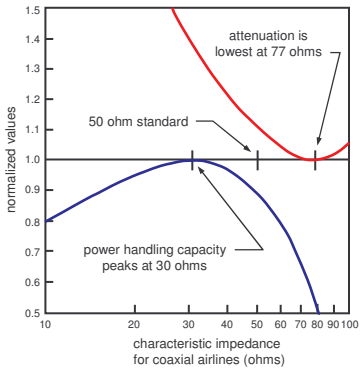
Transmission line Zo

- Zo determines relationship between voltage and current waves
- Zo is a function of physical dimensions and ε_r
- Zo is usually a real impedance (e.g. 50 or 75 ohms)





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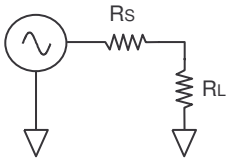
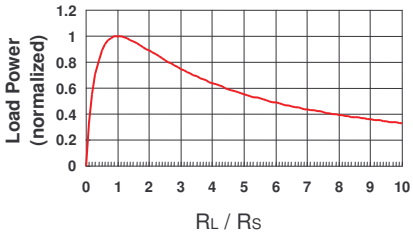
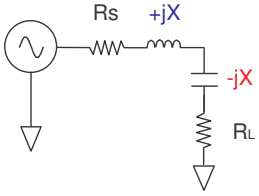
Power Transfer Efficiency





For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)



Maximum power is transferred when $R_L = R_S$

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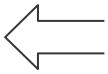
Transmission Line Terminated with Zo

Zo = characteristic impedance of transmission line

Zs = Zo

V_{inc}



$V_{refl} = 0$! *(all the incident power is absorbed in the load)*

For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

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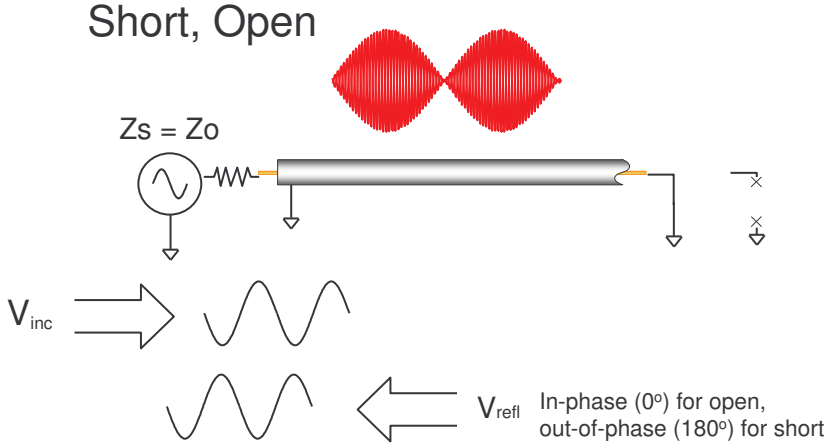
Transmission Line Terminated with Short, Open



For reflection, a transmission line terminated in a short or open reflects all power back to source

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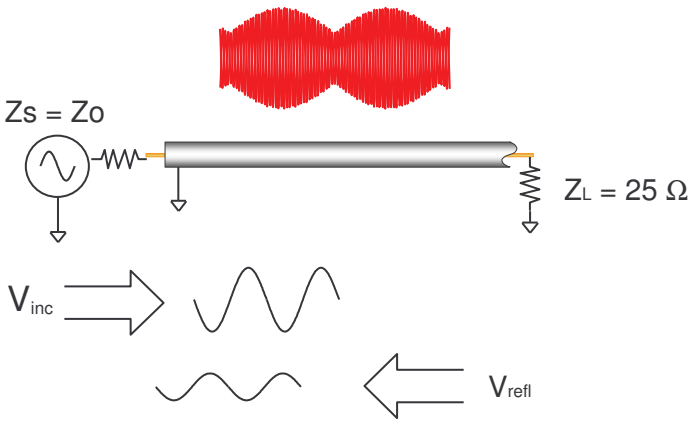
Transmission Line Terminated with 25 Ω



Standing wave pattern does not go to zero as with short or open

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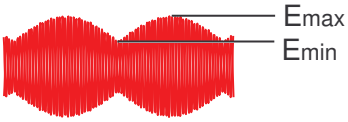
Reflection Parameters

Reflection Coefficient $\Gamma = \frac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \frac{Z_L - Z_O}{Z_L + Z_O}$

Return loss = -20 log(ρ), $\rho = |\Gamma|$



Voltage Standing Wave Ratio **VSWR** $= \frac{E_{max}}{E_{min}} = \frac{1 + \rho}{1 - \rho}$

No reflection (Z_L = Zo)		***Full reflection (Z_L = open, short)***
0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

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Transmission Parameters

Transmission Coefficient $= T = \frac{V_{Transmitted}}{V_{Incident}} = \tau \angle \phi$

Insertion Loss (dB) $= -20 \text{ Log} \left| \frac{V_{Trans}}{V_{Inc}} \right| = -20 \log \tau$

Gain (dB) $= 20 \text{ Log} \left| \frac{V_{Trans}}{V_{Inc}} \right| = 20 \log \tau$

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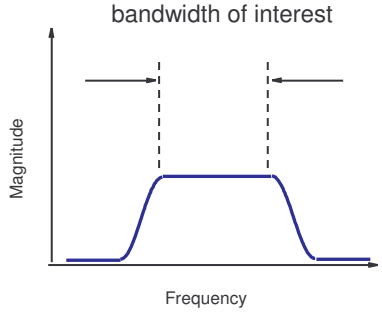
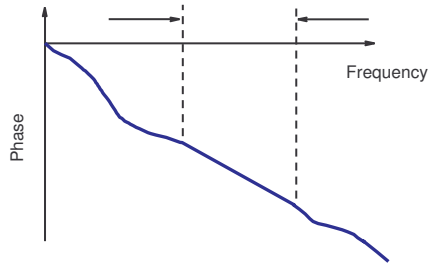
Criteria for Distortionless Transmission
Linear Networks

Constant amplitude over bandwidth of interest



Linear phase over bandwidth of interest



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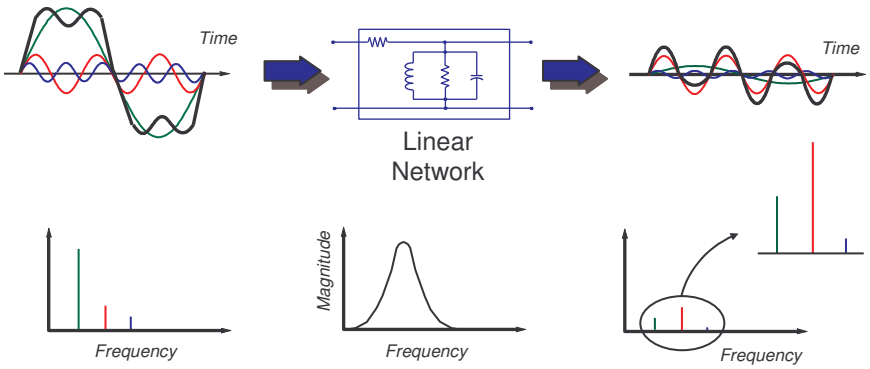
Magnitude Variation with Frequency

F(t) = sin wt + 1/3 sin 3wt + 1/5 sin 5wt



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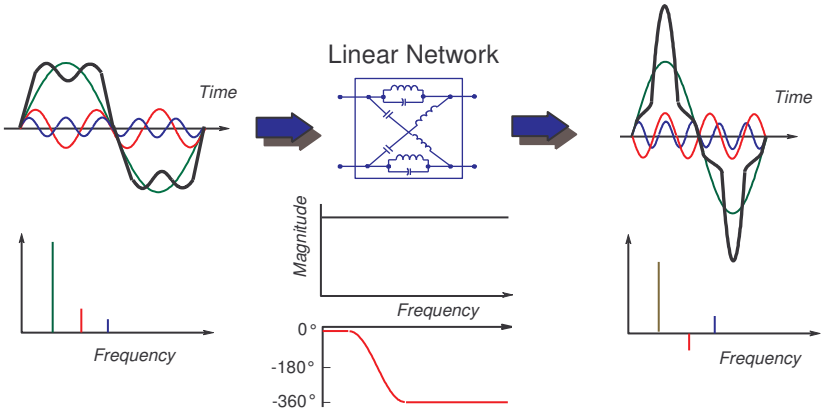
Phase Variation with Frequency

F(t) = sin wt + 1 /3 sin 3wt + 1 /5 sin 5wt



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Scattering parameters

Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

- gives linear behavioral model of our device
- measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- compute device parameters from measured data
- predict circuit performance under any source and load conditions

H-parameters	***Y-parameters***	***Z-parameters***
$V_1 = h_{11}I_1 + h_{12}V_2$	$I_1 = y_{11}V_1 + y_{12}V_2$	$V_1 = z_{11}I_1 + z_{12}I_2$
$I_2 = h_{21}I_1 + h_{22}V_2$	$I_2 = y_{21}V_1 + y_{22}V_2$	$V_2 = z_{21}I_1 + z_{22}I_2$

$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$ *(requires **open circuit**)*

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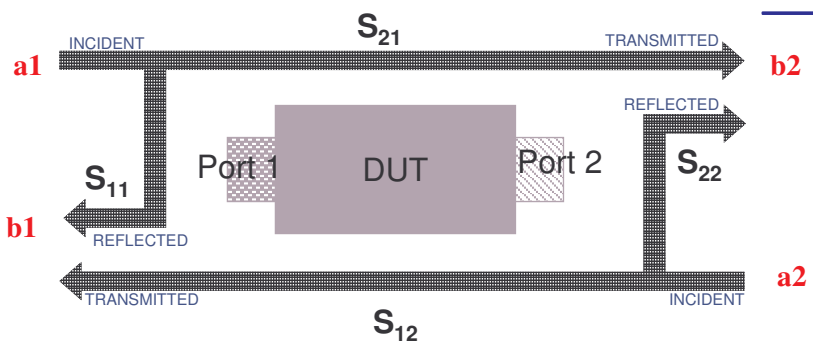
S-Parameters



$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

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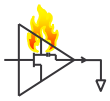
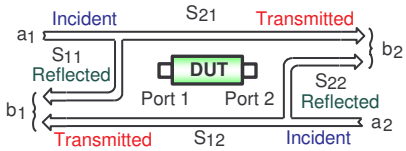
Why Use S-Parameters?



- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools



$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

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Equating S-Parameters with Common Measurement Terms

S11 = forward reflection coefficient ***(input match)***
S22 = reverse reflection coefficient ***(output match)***
S21 = forward transmission coefficient ***(gain or loss)***
S12 = reverse transmission coefficient ***(isolation)***

Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format

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S-Parameter Conventions

$$S_{21}$$

Signal Measured Here
(Out of DUT)

Signal Incident Here
(In to DUT)

Reflection Measurements = Numbers are the Same ; S_{11}, S_{22}
Transmission Measurements = Numbers are Different; S_{21}, S_{12}

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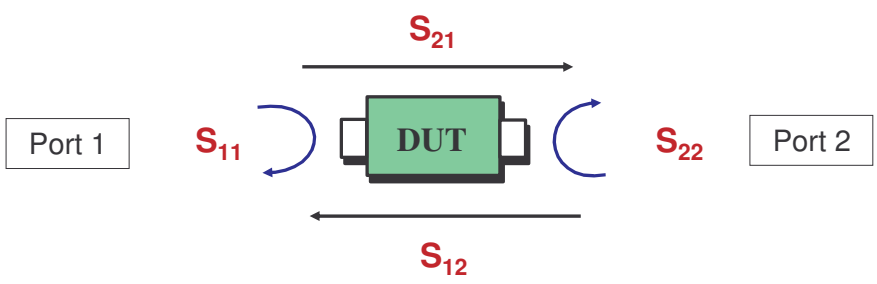
S-Parameters of a Two-Port Device



Completely characterize a two port device with four S-parameters

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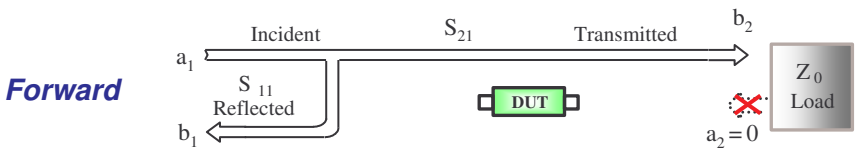
Define and Measure Forward S-Parameters



$$S_{11} = \frac{Reflected}{Incident} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$S_{21} = \frac{Transmitted}{Incident} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

$$b_1 = S_{11}\, a_1 + S_{12}\, a_2$$
$$b_2 = S_{21}\, a_1 + S_{22}\, a_2$$

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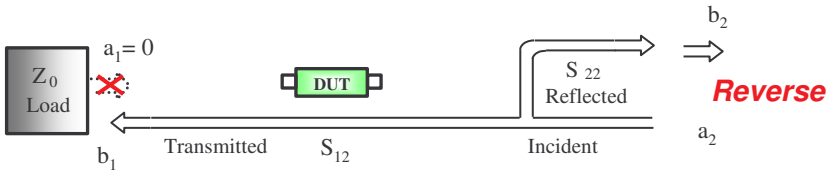
Define and Measure Reverse S-Parameters



$$S_{22} = \frac{Reflected}{Incident} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

$$S_{12} = \frac{Transmitted}{Incident} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

$$b_1 = S_{11}\, a_1 + S_{12}\, a_2$$
$$b_2 = S_{21}\, a_1 + S_{22}\, a_2$$

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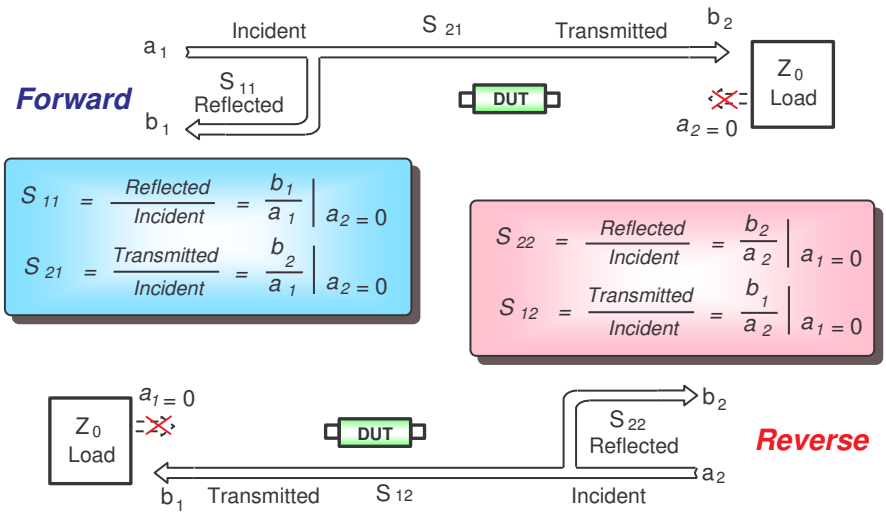
Measuring S-Parameters



$$S_{11} = \frac{Reflected}{Incident} = \frac{b_1}{a_1}\Big|_{a_2=0}$$

$$S_{21} = \frac{Transmitted}{Incident} = \frac{b_2}{a_1}\Big|_{a_2=0}$$

$$S_{22} = \frac{Reflected}{Incident} = \frac{b_2}{a_2}\Big|_{a_1=0}$$

$$S_{12} = \frac{Transmitted}{Incident} = \frac{b_1}{a_2}\Big|_{a_1=0}$$

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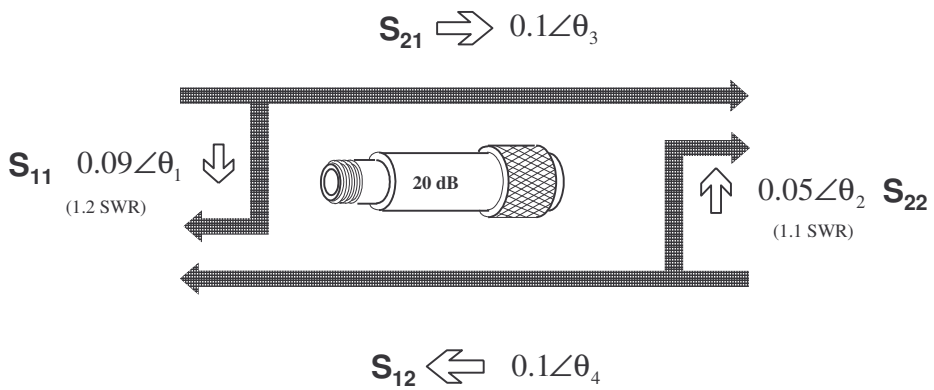
Attenuator S-Parameters



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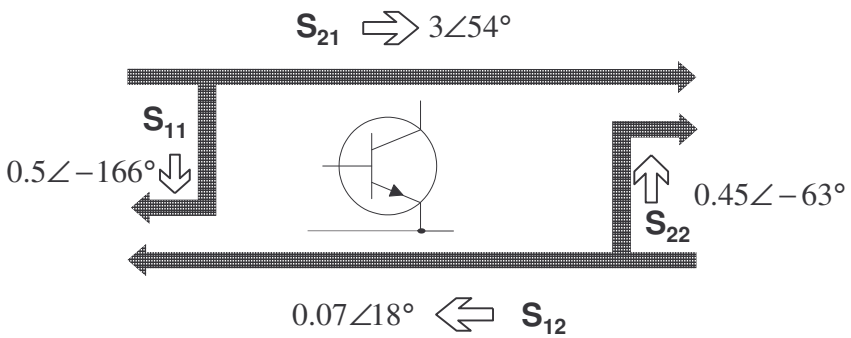
Transistor S-parameters



2N5103 @ 1 GHz

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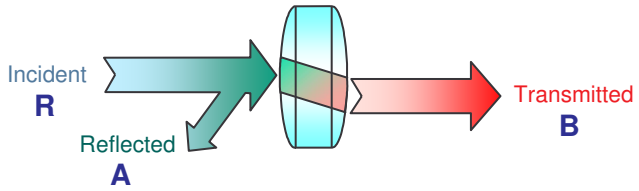
High-Frequency Device Characterization



REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

SWR

S-Parameters S_{11}, S_{22}

Reflection Coefficient Γ, ρ

Impedance, Admittance R+jX, G+jB

Return Loss

TRANSMISSION

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

Gain / Loss

S-Parameters S_{21}, S_{12}

Transmission Coefficient T, τ

Insertion Phase

Group Delay

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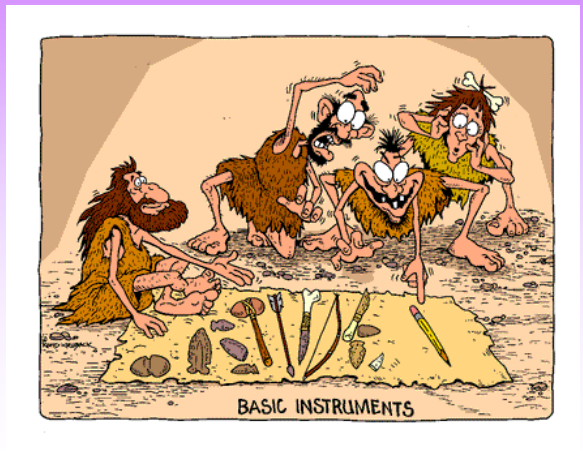
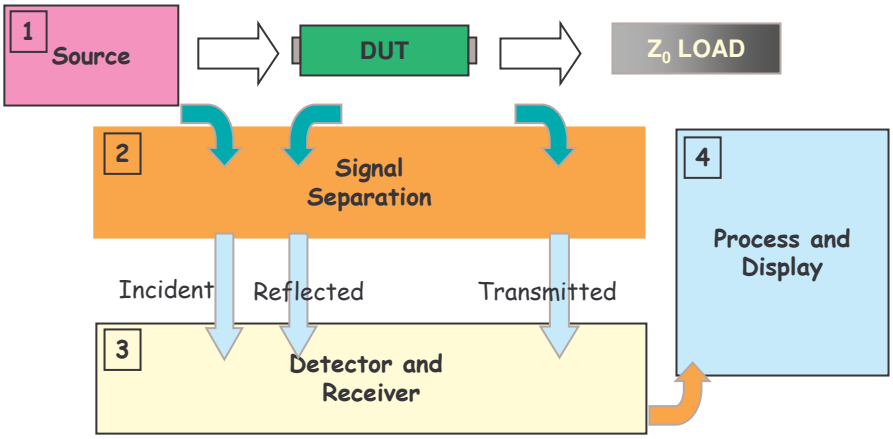
Modern VNA



Network Analyzer
the four blocks



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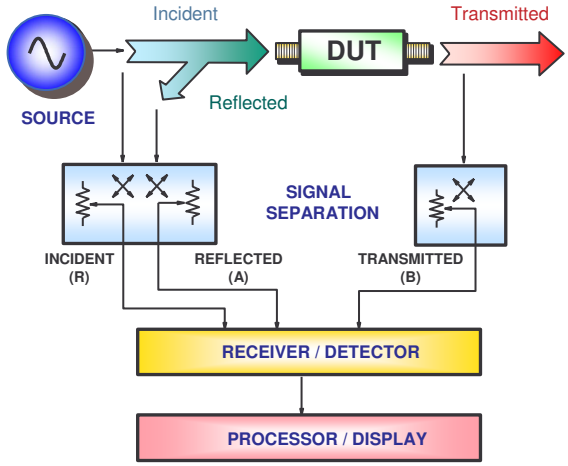
Generalized Network Analyzer Block Diagram



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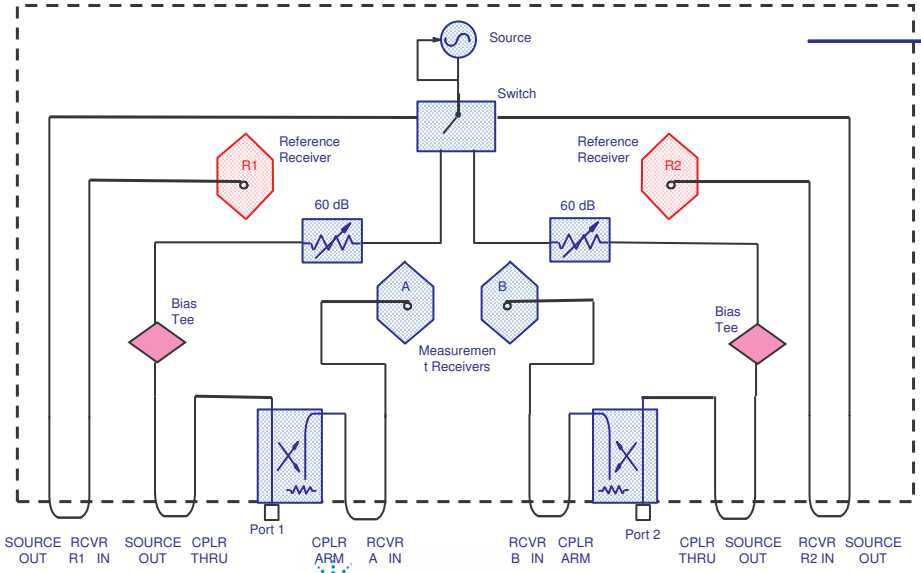
Full S-Parameter Test



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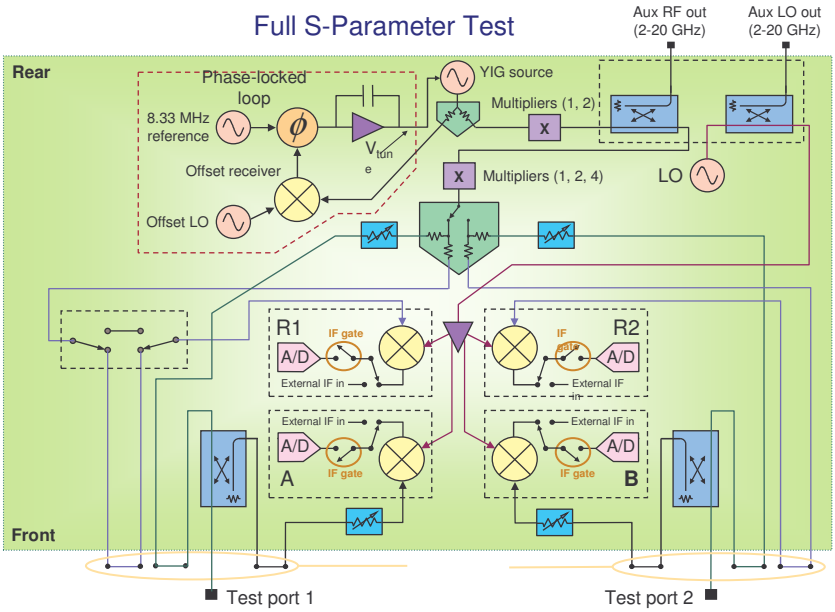
Full S-Parameter Test



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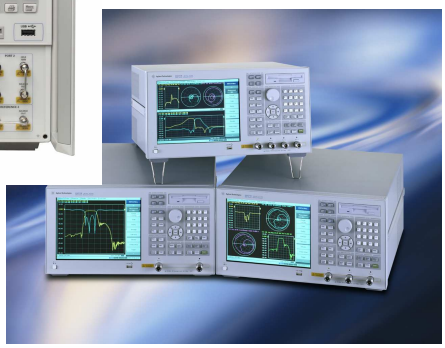
Network Analyzer Overview



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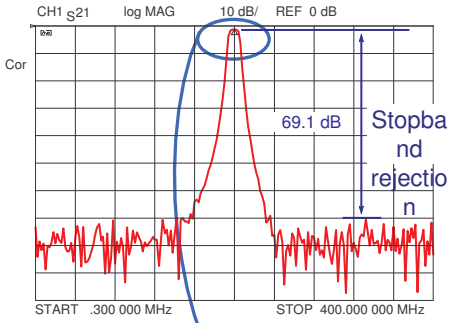
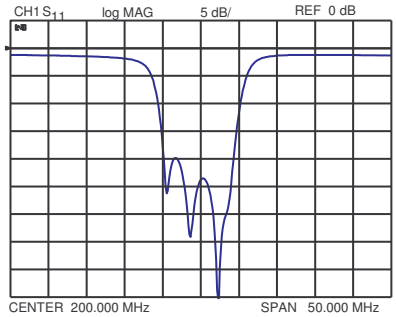
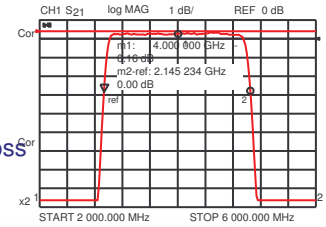
Frequency Sweep - Filter Test





Return loss



Insertion loss

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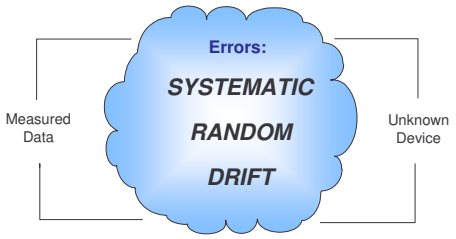
Calibration and error correction

Measurement Error Modeling

Systematic errors
- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

Random errors
- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors
- due to system performance changing ***after*** a calibration has been done
- primarily caused by **temperature variation**



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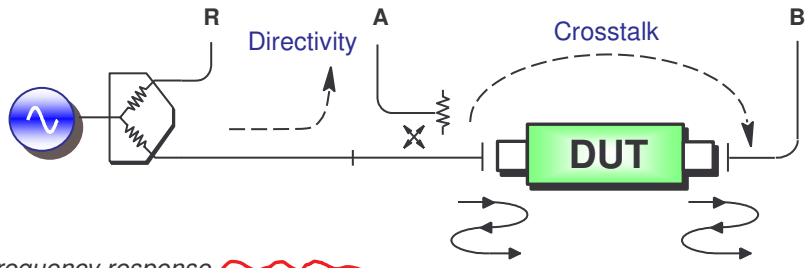
Systematic Measurement Errors



Frequency response
- reflection tracking (A/R)
- transmission tracking (B/R)

Six forward and six reverse error terms yields 12 error terms for two-port devices

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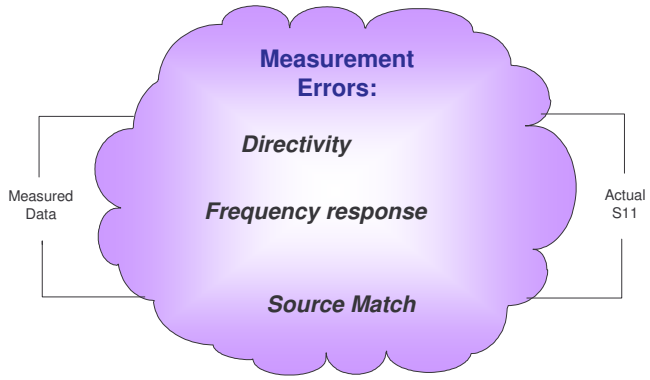
Major source of errors (I)

REFLECTION MEASUREMENTS



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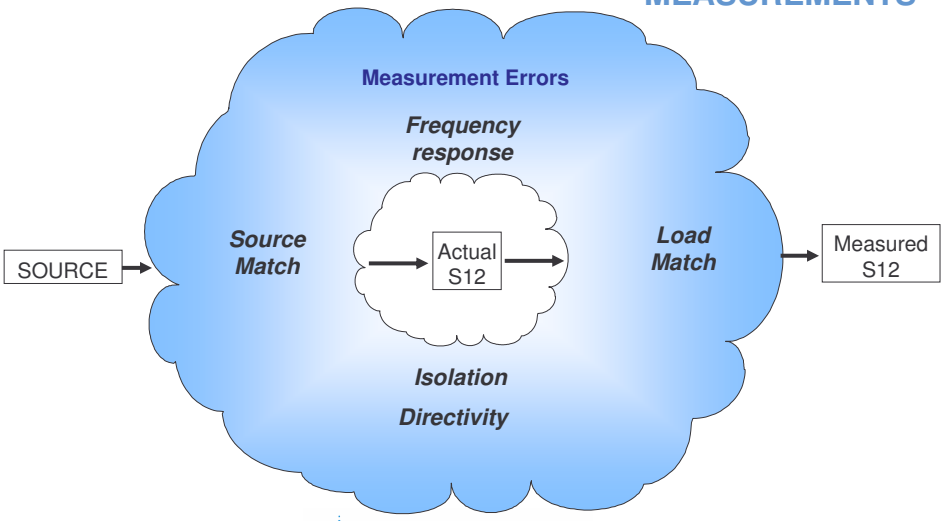
Major source of errors (II)

TRASMISSION MEASUREMENTS



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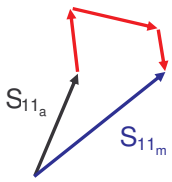
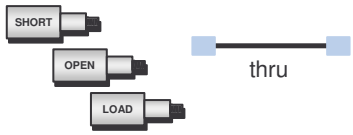
Types of Error Correction

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





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What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements
- **1-port calibration** *(reflection measurements)*
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT: Short Open Load Thru)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit

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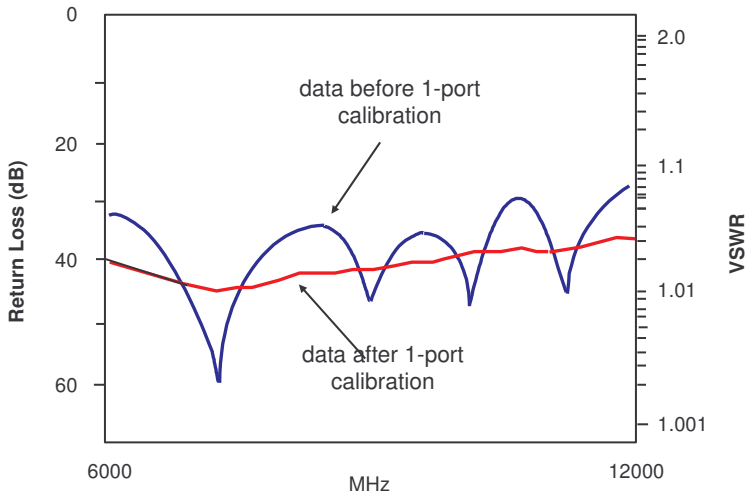
Before and After One-Port Calibration



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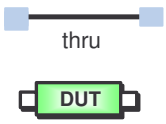
Errors and Calibration Standards

UNCORRECTED

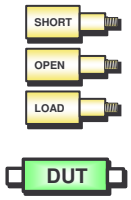
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



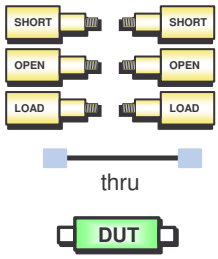
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

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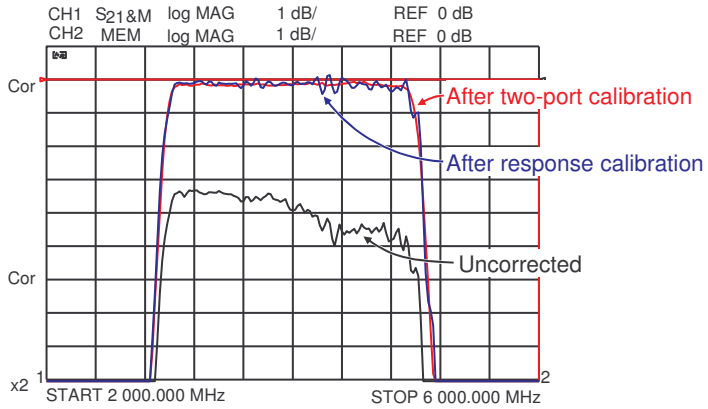
Response versus Two-Port Calibration

Measuring filter insertion loss



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Conversion to dB scale (I)

A convenient form to express large power or voltage ratios is to use "dB scale," based on logarithms.

$$dB = 20\log\left(\frac{V_2}{V_1}\right) = 10\log\left(\frac{P_2}{P_1}\right)$$
$$= 20\left(\exp_V\right) = 10\left(\exp_P\right)$$

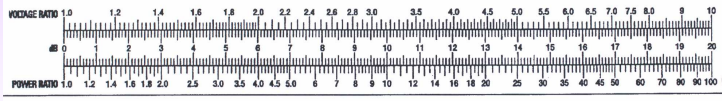
Where, V_1, V_2, P_1, and P_2 are the quantities to be compared, assuming equal terminations

The terms $\exp_V$ and $\exp_P$ are the 10-based exponents of the voltage and power ratios.

When dB is given, the conversions are:

$$\frac{V_2}{V_1} = 10^{\frac{dB}{20}} \quad \text{and} \quad \frac{P_2}{P_1} = 10^{\frac{dB}{20}}$$

VOLTAGE			POWER	
Ratio	Expon.	dB value	Expon.	Ratio
1	10^{0}	0	10^{0}	1
1.41	$10^{0.15}$	3	$10^{0.3}$	2
1.73	$10^{0.24}$	4.77	$10^{0.477}$	3
2	$10^{0.30}$	6	$10^{0.6}$	4
3.16	$10^{0.50}$	10	10^{1}	10
7.07	$10^{0.85}$	17	$10^{1.7}$	50
10	10^{1}	20	10^{2}	100
0.707	$10^{-0.15}$	-3	$10^{-0.3}$	0.5
0.5	$10^{-0.30}$	-6	$10^{-0.6}$	.25
0.316	$10^{-0.50}$	-10	10^{-1}	.1
0.1	10^{-1}	-20	10^{-2}	0.01



Summary

Expressing voltage and power ratios in dB simplifies the algebra since multiplication is reduced to addition, and division to subtraction.

To convert exponential power ratio to dB, multiply the exponent by 10.

To convert exponential voltage ratio to dB, multiply the exponent by 20.

Conversion to dB scale (II)

We use "**dB**" to simplify ratios.
The term "**dBm**" refers to an absolute power level.
"**0 dBm**" is used as a power reference level, defined to 1mW power dissipated in a resistive termination.

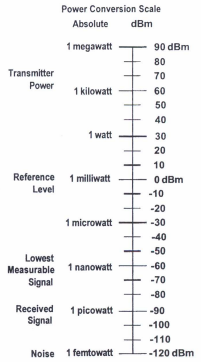
The "**dBW**" scale uses 1W as a reference instead of 1mW. Zero dBW is a power level of 1W.

To find dBm or dBW of an arbitrary power level:

$$\mathbf{dBm = 10\ log(P_{mW})} \quad \text{and} \quad \mathbf{dBm = 10\ log(P_W)}$$

To get Watts or milliWatts from dBm or dBW:

$$P_{mW} = 10^{\frac{dBm}{10}} \quad \text{and} \quad P_W = 10^{\frac{dBW}{10}}$$



Summary

Power reference scale in dBm and dBW

Abs. Power:	1nW	10nW	.1µW	1µW	10µW	.1mW	1mW	10mW	.1W	1W	10W	.1kW	1kW
dBm:	-60	-50	-40	-30	-20	-10	0	+10	+20	+30	+40	+50	+60
dBW:	-90	-80	-70	-60	-50	-40	-30	-20	-10	0	+10	+20	+30

Changing units of power (fW → pW → nW → µW → mW → W → KW → MW) always refers to a factor of 1000, or 10^3. Therefore, on the db (or dBm) scale, the corresponding change is always 30 dB (or dBm).

Sometime it is more convenient to use voltage for reference. The "dBV," "dBmV," and "dBµV" scales are referenced to 1V, 1mV, or 1µV applied to a specific resistor. For example, 0dBmV/75Ω refers to 1mV across 75Ω. Or, +20dBµV / 50Ω means 10µV applied to a 50Ω resistor (remember to use 20log, not 10log in the computation).